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Façade photovoltaic systems on multifamily buildings: An urban scale evaluation analysis using geographical information systems

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A B S T R A C T

In this paper is presented the application of a comprehensive methodology for the prediction of the photovoltaic (PV) potential in building façade surfaces and particularly with an application example for the Greek residential sector. The methodology is based on the determination of typical façade PV installations for Greek multifamily buildings considering architectural and technical aspects. The proposed solutions are then evaluated with dynamic energy simulation to determine the most efficient ones. The results produced in this way are used as baselines for a large scale analysis, which is implemented in the urban area of Greece's second largest city, Thessaloniki, by means of Geographical Information Systems. This led to the exploitable PV potential and the solar electricity production as well as the respective CO_2 savings. One of the interesting findings is the discrepancy between the architectural availability and the overall solar suitability of façade surfaces. This discrepancy is based on the following main factors: firstly, the high density of the built environment consisting of street canyons with high Height-Width ratio, secondly the varying orientation of the buildings and, finally, the buildings' typology, with the complex geometry due to verandas, erkers and semi-enclosed spaces.

Contents

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1. Introduction

The diffusion of residential photovoltaics (PVs) in Greece was slow until 2009, since no authorization and construction regulations or particular incentives were specified, until a national development programme was introduced, namely the Law 3734/2009. This provided potential investors with a remarkably high, tax-free tariff and clarified and simplified grid-connection procedures. Since then, the development of residential PV installations was immediate with over 50,500 applications (480 MWp approximately) submitted in four years to the Distribution System Operator (DSO) for grid-connection. Among these applications, over 37,600 were already put into operation in 2013, representing a cumulative capacity of 360 MWp [1].

The remarkable diffusion of solar PV energy in the Greek building sector during the last years inspired and motivated the main scope of the present paper. Building integrated (BIPV) and building applied (BAPV) photovoltaic systems, in other words PVs which replace conventional building materials and PVs installed as a retrofit to the building long after its construction respectively, represent the main subject of this paper. This study stands for a small but significant part of an extended assessment of energy saving retrofit measures for typical Greek urban regions and particularly the existing residential sector [2]. More specifically, the primary objective concerned the application of a comprehensive methodology to predict the PV potential of available areas on façades and particularly for residential multifamily (MF) buildings, as those represent the dominant building typology in the Greek urban areas [3]. The individual findings were then extrapolated to the core urban area of Greece's second largest city, Thessaloniki, by taking advantage of Geographical Information System (GIS) tool.

The methodology applied was consisted of three phases (Fig. 1) and foresaw initially the classification of typical buildings, as suggested by Theodoridou et al. [4], which led to typical constructional characteristics and allowed concluding about the best fitting and most suitable BIPV or BAPV systems. There are two main parameters that determine mostly the potential of PV systems on façade surfaces. The first refers to architectural and solar aspects, whereas the second to technical and legislative issues. In what concerns the architectural and solar aspects, there are two more criteria-steps of analysis affecting and examining the suitability of the building façades for PV applications:

(a) the morphology of the façade itself and the projections, such as balconies, which are the main façade element and,

(b) the surrounding urban environment's layout, in other words the adjacent street's direction and width combined with the volumes and heights of the opposite buildings and the neighboured buildings with their projections and shape. This criterion influences basically the shading effect, which should be limited in order to obtain high amounts of solar energy.

Obviously in the present paper, the combination of all the above elements was considered for the prediction of the PV potential both for the MF-buildings on individual level and for the city of Thessaloniki on urban level. The examination of the façades' typical morphology led to the most architecturally optimal façade PV applications for the MF-buildings. Various PV solutions were elaborated in terms of typical architectural configurations of the façades, by conducting for that purpose an extensive field research on a vast MF-building sample in the case study area. At this point, the buildings were studied independently from their built environment.

The proposed façade PV solutions were then evaluated by means of dynamic energy simulation, both to estimate the final energy and CO_2 savings when applied in MF-buildings and to assess their economic profitability. This led to the most optimal and efficient system, which was particularly examined in the urban scale analysis.

Finally, by using the GIS utilities for the case study urban area, the individual findings for the façade PVs on each MF-building were linked with the respective building units in the GIS maps, while the shading effects of the surrounding built environment were predicted with an empirical rule. The obtained outcomes determined ultimately the solar suitable façade areas and the associate PV potential.

2. Evaluation of typical façade PVs for the MF-buildings

In Greece the dominant building typology of the urban built areas is residential, and mostly consisting of MF-buildings, thus the integrated PV systems for the urban built environment should be linked to integrated PV systems' solutions, exclusively studied for the MF-building typology. The MF-buildings in Greece are called *"Polykatoikies"*. The typical morphological characteristics of Greek *"Polykatoikies"* are the balconies, the movable awnings and the Pilotis floor [5]. In particular, balconies are constructed as an extension of the interior floors/ceilings. Depending on the climatic

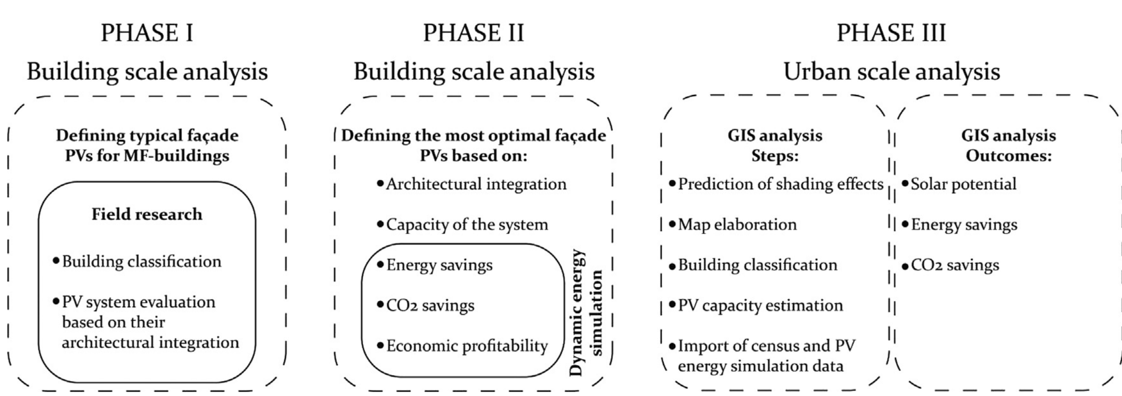

Fig. 1. Methodological approach in the present work.

Nomenclature

A_{af}	architecturally suitable area fraction
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAPV	building applied photovoltaics
BIPV	building integrated photovoltaics
CO_2	carbon dioxide
d	street's width
DHW	domestic hot water
DSM	Digital Surface Model
DSO	Distribution System Operator
DTM	Digital Terrain Model
DXF	Drawing Interchange Format
ETRS89	European Terrestrial Reference System 1989
Fac_{width}	façade's width
FiT	feed-in tariff
G_a	gross area
GEOBIA	Geographic Object-Based Image Analysis
GIS	Geographical Information System
HSA	Horizontal Solar Angle
h_{io}	the height of the opposite structure to the building unit across the street
HTRS07	Hellenic Terrestrial Reference System 2007
KENAK	Greek Regulation on Energy Efficiency of Buildings
MF	multifamily
MPP	maximum powerpoint
NOCT	Nominal Operating Cell Temperature
Nr.	number
PVs	photovoltaics
S_a	solar architecturally suitable areas
Sh_a	shaded façade area
shp	shapefile
SPB	Simple Payback Period
SQL	Structured Query Language
TOTEE	National Technical Directives
U-values	thermal transmittance values
VS	Sky View Factor
VSA	Vertical Solar Angle
γ	the façade's azimuth (orientation) related to north-south direction
γ_s	the solar azimuth for a specific time during the day
δ	the annual solar declination
θ_z	the zenith angle
ω	the daily solar declination

zone and their size, they are used for 3 to 5 months on an annual basis as a free recreational space zone. Moreover, *"Polykatoikies"* are shaded by overhangs (balconies) and awnings that are attached to them usually at an inclination of 45° (Fig. 2). In some cases they also have a Pilotis floor, namely a 3–4 m high open ground floor, which is mostly used as a parking space. The conventional construction materials used in MF-buildings consist mainly of reinforced concrete for the load bearing structure, whereas brick is implemented on internal and external walls, such as cavity walls [5].

A field research was conducted prior to the examination of technical and legislative issues. More specifically, according to each building's date of construction, a suitability evaluation was carried out, studying the harmonic integration of state of the art PV technology on typical façades. Hence, the examined buildings were initially classified based on the typological classification, as proposed by Theodoridou et al. [4], then certain solutions of BAPV or BIPV systems or even their combinations were proposed. The principle criteria of the overall PV selection were related to the high energy performance of PVs combined with the enhancement of architectural aesthetics of the MF-buildings. The primary objective of this study was a careful selection of the examined MF-buildings, in order to embody the main typological characteristics of the Greek *"Polykatoikia"*.

As regards the case study area, the urban area of Thessaloniki has two major municipalities, Thessaloniki and Kalamaria. Table 1 indicates the high density of the built environment in the Municipality of Thessaloniki by means of the total aggregate of the buildings regardless of their use. On the contrary, low built densities are observed for the area of Kalamaria, where the majority of buildings are constructed after 1980.

To ensure valid and representative measurement results, a large precinct of Thessaloniki's urban region was audited, while

Fig. 2. Typical elements of "*Polykatoikia*"; balconies (left), movable awnings (middle) and Pilotis floor (right).

a registration table was formed (Table 2), which allowed the classification of the façades according to certain architectural criteria, assumed to affect the PV implementation potential. In that specific table, the amount of exposed façades were recorded in accordance with the built form, namely the attached (row-system), semi-detached or detached construction system. Only the buildings with south, southeast and southwest street-facing façades were included in the sample. Thereafter, each building's façade was measured for its opaque and transparent surfaces. Moreover, the orientation of each façade along with the total gross area (G_a) was registered. In addition to this generic data, details about the length and width of the balconies as well as the height of the safety parapets were noted. Thereafter, the availability of the exposed construction elements was also recorded. Finally, for buildings with façades on two streets, with desirable near south orientation, the procedure was repeated for both. Subsequently to the inventory of all opaque surfaces' related information, the transparent elements (glassdoors and windows) were measured as well. It should be remarked that the existing shading devices, such as awnings, were not registered, since BIPV awnings and louvers concern an application with great potential for MF-buildings. Besides, in cases they will be utilized, they replace the existing conventional shading systems regardless of their size and shape. As far as solar architectural suitability of façades was concerned, the shading effects from the built environment were approximated by applying the empirical algorithm described in the next section.

After collecting the appropriate data, a thorough elaboration was performed in order to conclude to standard feasible PV applications, based on the date of construction and the respective architectural façade features of the examined MF-buildings. The analysis regarded four typical classes of residential MF-buildings in Greece, taking into account both their actual and modelled energy performance. These classes are associated with the constructions dated between 1960 and 1980 (Class B2), 1981–1990 (Class C) and 1991–2010 (Class D) [4]. The typical structures refer to MF-buildings and are organized as shown in Table 3. The first MF building (MF1) was constructed in 1969 and is located in the city centre, namely the Municipality of Thessaloniki. The second one was constructed in 1976 and is located in the Municipality of Kalamaria. Building MF1 represents a typical row system construction, whilst building MF2 is a detached construction with pilotis on the ground floor. Additionally, building MF3 was constructed in 1985 in attached built form, whereas the Class D, that is to say the latest residential constructions (1990–2010), was evaluated by means of the detached building MF4, construction of which was dated back to 1998. The last two buildings are both located in the region of Kalamaria. Five additional subcategories were also developed, including a more detailed built form of the examined MF-buildings as shown both in Table 4. These subcategories assisted the urban scale analysis, as the individual buildings' PV results could be directly and accurately linked with the whole residential building stock.

Table 1
Amount of buildings with residential mixed and exclusive use classified based on the date of construction in the Municipalities of Thessaloniki and Kalamaria [3,4].

Building Class	Class A	Class B		Class C	Class D
		Class B1	Class B2		
Date of construction	pre 1945	1946–1960	1961–1980	1981–1990	post 1991
Municipality of Thessaloniki	2560	3097	11,798	3485	2386
Municipality of Kalamaria	193	576	2515	2190	1183

Table 2
Registration table of façade configuration features used in the present field research.

Date of the construction											
Building class similar to		MF1/MF2/MF3/MF4									
Nr. of the exposed façades											
FAÇADE 1 – opaque surfaces											
Orientation of the façade		S/SW/SE									
Gross (G_a) area (m^2)											
Dimension of balconies (m)		Balconies at full length of façade	Exposed load bearing structure elements		Dimension of balconies (m)			Number of available load bearing structure elements	Type of load bearing structure elements	Load bearing structure dimensions (m)	
width	length	Yes/No	Number	Position	width	height	length			width	height
FAÇADE 1 – openings											
Orientation of façade			S/SW/SE								
Total area of glass doors (m^2)			Total area of windows (m^2)			Sum of openings (m^2)					

Table 3
Examined MF-buildings [2,5].

	Class B2 (1960–1980)		Class C (1981–1990)	Class D (1991–2010)
Code name	MF1	MF2	MF3	MF4
Date of construction	1969	1976	1985	1998
Built form	Attached (row-system)	Detached with Pilotis	Attached (row-system) with Pilotis	Detached with Pilotis

The examined building sample included a vast variety of MF-buildings to ensure representative outcomes for the façade architectural practices. Multiple typologies were audited, continuously discriminated based on the four typical MF-buildings and their respective sub-categories presented in previous tables. Overall, the amount of the registered buildings was compared to the total sum of buildings of the case study areas (Table 5).

Aiming at drawing conclusions about the architecturally most optimal façade PV applications, the obtained measurements were firstly elaborated in terms of the façades' architectural morphology. Attention was laid upon the determination of the common characteristics of the façades for each building class. In particular, Fig. 3 illustrates the main architectural typology features of MF-buildings. It is noted that buildings constructed before 1960, were either influenced by the neoclassical trend or the new-modern movement. In both cases, balconies rarely expand over the whole façade. They are mostly of shorter lengths and widths, whilst decorative architectural projections are a common practice. After 1960, the typological features embodied several architectural features of a different, albeit lower, aesthetic quality. The balconies are elongated in alignment to the projection of the façades, while their width is increased as well. This was a result of promoting more efficient constructions, by means of anti-seismic measures that reached the present formation by the introduction of the Anti-seismic Code of 1954 after several revisions. Finally in the case of Class D (after 1990), the balconies were recorded to vary in length mainly for architectural purposes, but most of them were constructed within the maximum permissible widths. Indicative perspectives of the building sample are shown in Fig. 4, with classes based on the date of construction. It is important to note that in Class B2 and Class C the windows are highly reduced with respect to the total openings' areas, at least as regards the street facing façades. In what concerns balconies, their shape was not only affected by the architectural trends, but also by the legislative constraints mostly associated with the seismic safety regulations. This is also verified by the field research; for Class A and B1, balconies rarely exceed the width of 0.80 m (Fig. 5). On the other hand, for Class B2 and Class C, the dominating balcony width is 1.20 m; while for Class D it gets wider, reaching 1.70 m.

The elaboration of the façades' typical architectural aspects eventually led to determining the potential of the architecturally most suitable areas for PV integration. More specifically, the replacement of the balcony's safety parapets and extended fabric or metal awnings with PVs, the cladding of the exposed load bearing structure elements with opaque PV modules and finally the use of vertical or horizontal PV louvers were assumed as the most appropriate BIPV applications. It is important to observe that Class A and B1 buildings were not included in the target groups of buildings available for PV installations, as they refer to landmark buildings. Therefore, the proposed solutions only regard Class B2, Class C, Class D buildings as well as recently constructed buildings (after 2010). The potential façade BIPV systems are illustrated by means of 2D graphics in Fig. 6.

It becomes clear that solution D requires a detailed architectural study prior to the PV implementation. The type of the shading devices should be precisely designed so as not to deteriorate indoor optical comfort or to reduce day-lighting levels and solar thermal gains in the winter period. A more flexible option

Table 4
Subcategories of building classes according to the buildings' construction system.

	Class B2	Class C		Class D	
Code name	MF1_sem.de	MF3_sem.de	MF3_de	MF4_sem.de	MF4_att
Built form	semi detached	semi detached	detached	semi detached	attached (row-system)

Table 5
The amount of the audited buildings classified according to the date of construction and compared to total number of the buildings based on the official data of the Hellenic Statistical Authority [1].

Total sum of buildings	Total sum of building blocks	Municipality of Thessaloniki				
		Class A	Class B1	Class B2	Class C	Class D
23,563	2253	2560	3097	11,798	3485	2386
Buildings audited		148	182	695	202	138
		Municipality of Kalamaria				
Total sum of buildings	Total sum of building blocks	Class A	Class B1	Class B2	Class C	Class D
6770	700	193	576	2515	2190	1183
Buildings audited		10	39	362	264	142

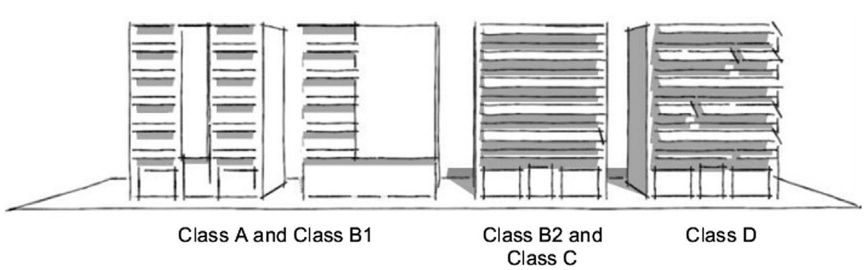

Fig. 3. Typical building façades according to the building class.

Fig. 4. Typological characteristics of the façades according to the MF-building classification.

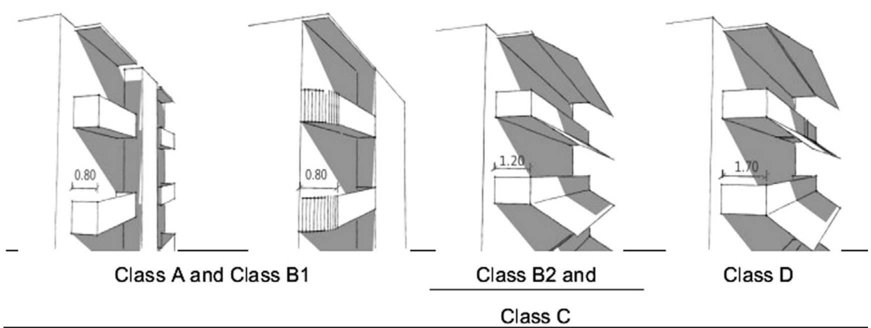

Fig. 5. Mean widths of balconies measured in the building sample according to the buildings' classification.

would be a solar tracking but it is a matter of the benefit-cost evaluation to determine its feasibility. In contrast to solution D, the other three solutions are rather more delicate, as they have implications on the building's aesthetics. With respect to the solution B, it is most likely that the PV modules will be shaded, especially during summer periods, from the building's own projections as well as from the adjacent buildings' façade elements, which are mainly in blocks with the row-system primary construction system. Besides, in over 50% of the examined sample, and concerning detached buildings, the balconies cover the façade's perimeter, posing even larger shading issues for the side load bearing structure. In that sense, solution B is not proposed as a viable one. A combination of these options is also possible for solutions A - C and A - D.

Conclusively, Table 6 depicts the averaged measurement results of the examined façade sample, while in correspondence with the proposed solutions depicted in Fig. 6, the architecturally suitable area fraction (A_{af}) was predicted for typical façades for each building class, as it is shown also by Table 7. This fraction leads to the overall solar architecturally suitable (S_a) areas, after applying an additional empirical rule for the estimation of the shading effects from the surrounding built environment, which is analysed thoroughly in the next section. As it is easily noticed, the maximum available façade areas were accounted for the combination of BIPV louvers with parapets, given that they can fully utilize the free open space between two successive floors. Still, the explicit fractions can only be obtained if the final design of the louvers is provided.

Before the urban scale analysis, significant target to reach was the determination of the most optimal façade PV installation for the MF-buildings, given that there are multiple proposed PV solutions available, as already discussed above. For that purpose, the following criteria had to be assessed:

(a) the degree to which the proposed systems can be harmonically integrated into the existing architecture of the MF-buildings, which can only be examined qualitatively,
(b) the potential PV capacities,
(c) the degree to which the final energy can be modified,
(d) the affordability of the investment capital needed and its respective payback period,
(e) the degree to which the CO_2 emissions can be altered and
(f) the overall annual energy performance of the PV systems.

To an extent, the first criterion was already examined above. In the following paragraphs the rest of them are evaluated by means of dynamic energy simulation.

3. Impact of the façade PVs on the energy performance of MF-buildings

3.1. Simulation process

The four MF-buildings presented in Table 3 and their additional five subcategories (Table 4) were simulated for the impact of the façade PVs on their energy performance. For that purpose, the dynamic building energy simulation tool EnergyPlus [8] was used along with the assumptions and the specifications for residential

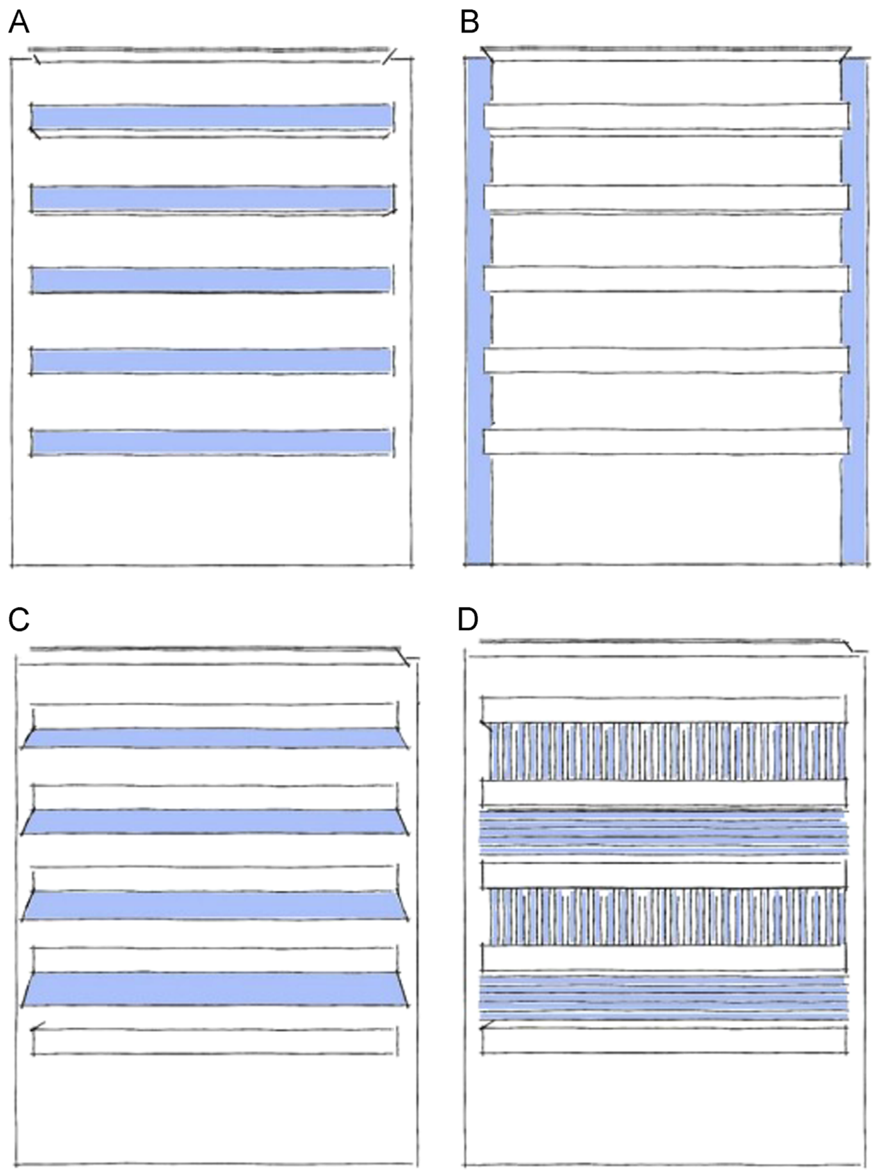

Fig. 6. Proposed solutions for potential façade PV systems in the MF-buildings. (A) Balcony BIPV parapets, (B) Cladding BIVP systems onto the exposed load bearing structure, (C) BIPV awnings, (D) Vertical or horizontal BIPV louvers.

Table 6
Averaged measurements of the façade sample.

Building Classes	Averaged façades' dimensions per floor		Averaged balconies' dimensions per floor		Averaged awnings' dimensions per floor	
	Height [m]	Width [m]	Width [m]	Length [m]	Width [m]	Length [m]
Class B2 (row-system) - MF1	3.00	11.90	0.80	8.20	1.00	8.20
Class B2 (detached) - MF2	3.00	16.10	0.80	12.90	1.00	12.90
Class C - MF3	3.00	16.00	1.20	14.00	1.00	14.00
Class D - MF4	3.00	17.70	1.70	13.20	1.00	13.20

buildings, set by the National Technical Directives (TOTEE) of the Greek Regulation on Energy Efficiency of Buildings (KENAK) [9–12].

The weather data used are the official climatic data for Thessaloniki, as published by ASHRAE [13,14]. Thessaloniki is generally characterized by a Mediterranean climate, with high humidity levels as it is situated by the sea, and belongs to the second coldest zone of Greece, i.e. the 3rd zone. The U-values of the building envelope elements and openings are shown in Table 8 and are in accordance with KENAK. Similarly, the infiltration and ventilation rates as well as the operational profiles of the buildings were set taking into account the standards of KENAK [9]. For the residential building typology, the operational schedules, the thermostatic control, the internal heat gains, the hot water demand as well as the ventilation loads were assumed to be similar for all MF-buildings (Table 9).

Regarding the input parameters and the assumption for the heating systems, they were examined using the actual efficiency of boilers provided by their annual maintenance report. However, the overall systems' efficiency had to also include the losses due to the distribution network, the over-dimensioning and the domestic hot water (DHW) boiler losses with respect to the respective Technical Guideline (TOTEE). Referring particularly to the over-dimensioning evaluation, the loss factor of the actual efficiency of the boilers was estimated independently from the consumed type of fuel. This was

Table 7
Architecturally suitable area fractions (A_{af}) for typical façades according to the building classes and the proposed PV solutions of Fig. 5.

Building Classes	Façade BIPV proposed solutions				
	BIPV parapets (A_{af}) (Solution A)	BIPV awnings (A_{af}) (Solution C)	BIPV louvers (A_{af}) (Solution D)	BIPV parapets and awnings (A_{af}) (Solutions A-C)	BIPV parapets and louvers (A_{af}) (Solutions A-D)
Class B2 (row-system) – MF1	18.38%	22.97%	35.37%	41.34%	53.75%
Class B2 (detached) – MF2	21.37%	26.71%	41.13%	48.07%	62.50%
Class C – MF3	23.33%	29.17%	44.92%	52.50%	68.25%
Class D – MF4	19.89%	24.86%	38.28%	44.75%	58.17%

Table 8
U-Values of the envelope's vertical and horizontal elements of the examined MF-buildings [10].

	Brick walls [W/m^{2}K]	Concrete elements [W/m^{2}K]	Flat roof [W/m^{2}K]	Pilotis [W/m^{2}K]
MF1	2.21	3.41	3.06	–
MF2	2.21	3.41	3.06	2.76
MF3	0.86	3.41	3.06	2.76
MF4	0.66	0.71	0.51	2.76
	Glazing [W/m^{2}K]		Frame [W/m^{2}K]	
MF1	Single glazing 5.70		Aluminium (no thermal break) 7.00	
MF2	Single glazing 5.70		Aluminium (no thermal break) 7.00	
MF3	Double glazing (6 mm) 3.30		Aluminium (no thermal break) 7.00	
MF4	Double glazing (12 mm) 2.80		PVC frame 2.80	

Table 9
Main characteristics regarding the operational profiles of the residential buildings according to KENAK [9].

Thermostatic control	Heating period [°C] 20	Cooling period [°C] 26
Ventilation	People per floor area 0.05	Natural ventilation [m^3/h/person] 15
Internal heat gains	People [W/person] 80	Mean occupancy coefficient 0.75
Internal heat gains	Equipment [W/m^2] 4	Mean operation coefficient 0.75
Domestic hot water demand[a]	DHW demand [m^3/bedroom/year] 27.3	Person/bedroom 1.5
Lighting	Illuminance [lux] 200	Nominal power [W/m^2] 3.6

[a] Data according to the revised TOTEE in 2011.

accomplished applying an empirical rule, defined by the TOTEE [9], which proposes a theoretical estimation of the appropriate heating system's capacity. The over-dimensioning assessment is based on parameters such as the building's envelope, its mean U-value according to the date of construction, the climatic zone and a correction coefficient of 1.8 introduced for the distribution losses, the intermittent operation of the heating system and the infiltration and ventilation loads. Similar assumptions were also made for the efficiency of the water heaters. In Table 10 the overall efficiency of the existing heating systems of the examined MF-building typologies are presented.

Last but not least, considering air-conditioning, consumptions are calculated according to KENAK, based on the assumption that 50% of the cooling load is dealt with split air-conditioning units and 50% with natural ventilation. This is an approximation which, especially in lower income areas, is a rather rough estimation given that there are apartments without air-conditioners or with only one room air-conditioner, leading possibly to an over-estimation of the respective simulated electricity consumptions [15].

3.2. Photovoltaic systems' parameters

In the EnergyPlus, the user can select among three different models for predicting the photovoltaics' performance; the “Simple”, the “Equivalent One-Diode” and the “Sandia” [16]. The “Sandia” model is the most accurate one, as it is based on empirical relationships with coefficients that are derived from actual testing of certain PV module operation. Thus, the coefficients are used to calculate five select points on the current-voltage curve of module. Consequently, this model was chosen for the present simulations. In Table 11 the main electrical and technical properties of the modelled PV module are shown. Its nominal efficiency is considered to be 14.4%. It should also be noted that within EnergyPlus the PV modules and arrays are assumed to operate at maximum power-point (MPP). Furthermore, the inverter efficiency is linearly used to derate the energy production [16]. The inverters' efficiency was set based on existing well-known devices' characteristics [17] and after their appropriate dimensioning in accordance with the capacity of each examined PV system.

Ultimately, as regards the PV module's operating temperature and since the proposed PV applications in the current paper were systems installed either on simple free-ventilated mounting racks or shading devices, the cell temperature of the PVs was modelled using the method of Duffie and Beckmann [18] or the so called “Decoupled NOCT (Nominal Operating Cell Temperature) Conditions” model. In other words, the module cell temperature was computed at each time step of the simulation based upon the standard NOCT values.

3.3. Simulation scenarios

The simulation scenarios were configured taking into consideration the proposed façade PV applications presented in Fig. 6. More specifically, nine PV scenarios were examined, which represent the different solutions of PV systems proposed for the façades of the typical MF-buildings. Overall, 81 scenarios were simulated for all nine MF-building typologies (Table 12).

Initially, PVpar scenarios foresaw the integration of opaque PV modules in balcony parapet structures. The systems were installed on the floors where the un-shaded areas were specifically identified during the winter solstice, after thorough shading modelling (Fig. 7). A similar task was carried out for all the examined façade

Table 10
Heating systems of the examined MF-buildings.

	Heating fuel	Actual efficiency [%]	Overall efficiency [%]	Over- dimensioning coefficient	Well insulated boiler shell	Well insulated heating distribution network
MF1	Oil	93.0	57.0	2.69	No	No
MF2	Natural gas	93.0	66.0	2.21	Yes	No
MF3	Oil	92.0	70.0	1.20	No	No
MF4	Natural gas	91.5	65.0	4.00	Yes	Yes

Table 11
Electrical and technical properties of the modelled PV module [16].

Properties	Value
Active area [m^2]	1.285
Nominal capacity [W]	185
Number of cells in series	12
Number of cells in parallel	6
Short circuit current [A]	5.5
Open circuit voltage [V]	44.9
Current at maximum power point [A]	5.12
Voltage at maximum power point [V]	36.2

PV applications. The PV parapets' capacities did not exceed 3.00 kWp, 7.80 kWp, 4.15 kWp and 4.60 kWp in MF1, MF2, MF3 and MF4 typologies correspondingly (Table 13).

PVawn and PVawn-trans scenarios included PV modules, both opaque and semi-transparent (10% transparency was simulated), integrated as awnings on the un-shaded floors of the MF-buildings. The PV awnings were designed at the optimal inclination of 30° and were assumed fixed throughout the year (Fig. 7). The capacities in MF1, MF2, MF3 and MF4 typologies were relatively greater than those of BIPV parapets; 4.25 kWp, 11.60 kWp, 6.50 kWp and 7.25 kWp respectively (Table 13).

PVawn_par and PVawn_par_trans scenarios referred to the combination of PV modules integrated as awnings and balcony parapets; namely a combination of PVawn and PVpar. The modules were examined separately as opaque and semi-transparent. In contradiction with the PVawn scenario, the awnings were modelled at an inclination of 90°, ensuring that they would not shade the BIPV parapets during the summer period (Fig. 7). Obviously the PV systems' sizes were obtained by the aggregate of PVawn and PVpar scenarios' aforementioned capacities (Table 13).

PVlouv and PVlouv_movable scenarios included BIPV louvers installed at a fixed inclination and equipped with a one-axis sun-tracking system respectively. Their design, as illustrated in Fig. 7, aimed at eliminating the reciprocal shading effects between their series during the summer period, while for the same reason, they were simulated at a 50° slope rather than at the optimal one for Thessaloniki's location. In these two scenarios the louvers were assumed to be opaque. Consequently, the BIPV louvers' capacities for MF1, MF2, MF3 and MF4 typologies did not exceed 2.65 kWp, 7.60 kWp, 5.45 kWp and 6.05 kWp correspondingly, sizes relatively limited compared to the PVawn cases (Table 13).

The last two, but of equal significance, studied scenarios included systems of BIPV louvers combined with BIPV parapets (PVlouv_par and PVlouv_par_trans scenarios). This led to a specific design according to which the BIPV louvers were installed at a fixed 90° inclination, as depicted in Fig. 7, and were modelled for both opaque and semi-transparent. The total PV capacities reached 7.60 kWp, 20.40 kWp, 13.45 kWp and 15.05 kWp for MF1, MF2, MF3 and MF4 typologies respectively, sizes greater than the ones approximated for the PVawn_par cases (Table 13).

The combinations of PV awnings or louvers with PV parapets represent apparently the largest capacities both in absolute values but also expressed per conditioned built area of the MF-buildings. From a first point of view, these three types of applications would probably be the most efficient in terms of energy savings and economic profitability. Still, this also has to be justified by the simulation results that follow.

3.4. Simulation results

The main simulation outcomes were distinguished between three aspects of potentials; at first the impact of PVs on the final energy consumptions of the MF-buildings were demonstrated by means of energy potential. Thereafter, the simple payback period of the systems was exemplified via the economic potential (feasibility), based on the impact of the PVs on the energy performance of the MF-buildings and the generated electricity fed into the grid. Ultimately, the primary energy consumptions and the associated CO_2 emissions were evaluated through the environmental potential. All these findings, as already mentioned, contributed to the determination of the most optimal façade PV solution for the MF-building classes in Greece.

3.4.1. Energy potential

Four kinds of consumptions were evaluated for the energy potential prediction; domestic hot water, electrical appliances and lighting systems, heating and lastly cooling. Initially the energy behaviour of the MF-buildings with applied PV installations was assessed without taking into account the electricity generated on an annual basis (Table 14). This allowed for emphasizing the effect of PVs on heating and cooling loads, as long as the PVs on façades operate also as shading devices. In that sense, the demand for DHW and electrical end uses were not altered at all.

Then, the existing final energy consumptions of the examined MF-buildings represented the base case scenario compared to which the overall energy savings by PVs were evaluated (Table 15). From the results it is obvious that the heating and cooling consumptions are more increased for the MF-buildings in detached or semi-detached built-form, despite of the building class. The maximum differences are reasonably observed between attached and detached units.

The selection of the optimal PV scenario in terms of energy potential should be a matter of maximizing the solar utilization factor of the available areas and the annual electricity production, while eliminating the negative effect on the final energy demands of the MF-buildings, especially on heating. The last parameter proved to be the determinant for the net energy savings accomplished by the PVs on the façades of the MF-buildings. The most beneficial PV applications can be determined by taking into account on the one hand the findings of Tables 13 and 14, and on the other hand the outputs of Fig. 8. At this point it should be noted that although the PV parapets have not any shading and cooling effect on the MF-buildings, their admittedly limited solar utilization factor for the available façade areas and their lower annual electricity generation rates make this option quite undesirable. Hence, the concluding review of the optimal PV applications

Table 12
The simulation scenarios, linked to the proposed PV applications (Fig. 5) and their attributed code name.

Proposed PV applications	Scenarios – code name	Description
Façades – Solution A	PVpar	PV opaque modules integrated in the balcony parapet structures
Façades – Solution C	PVawn	PV opaque modules integrated as awnings
	PVawn_trans	PV semi-transparent modules integrated as awnings
Façades – Solution A-C	PVawn_par	A combination of PV opaque modules integrated as awnings and balcony parapets
	PVawn_par_trans	A combination of PV semi-transparent modules integrated as awnings and balcony parapets
Façades - Solution D	PVlouv	PV opaque modules integrated as louvers
	PVlouv_movable	PV opaque modules integrated as movable one-axis sun-tracking louvers
Façades – Solution A-D	PVlouv_par	A combination of PV opaque modules integrated as louvers and balcony parapets
	PVlouv_par_trans	A combination of PV semi-transparent modules integrated as awnings and balcony parapets

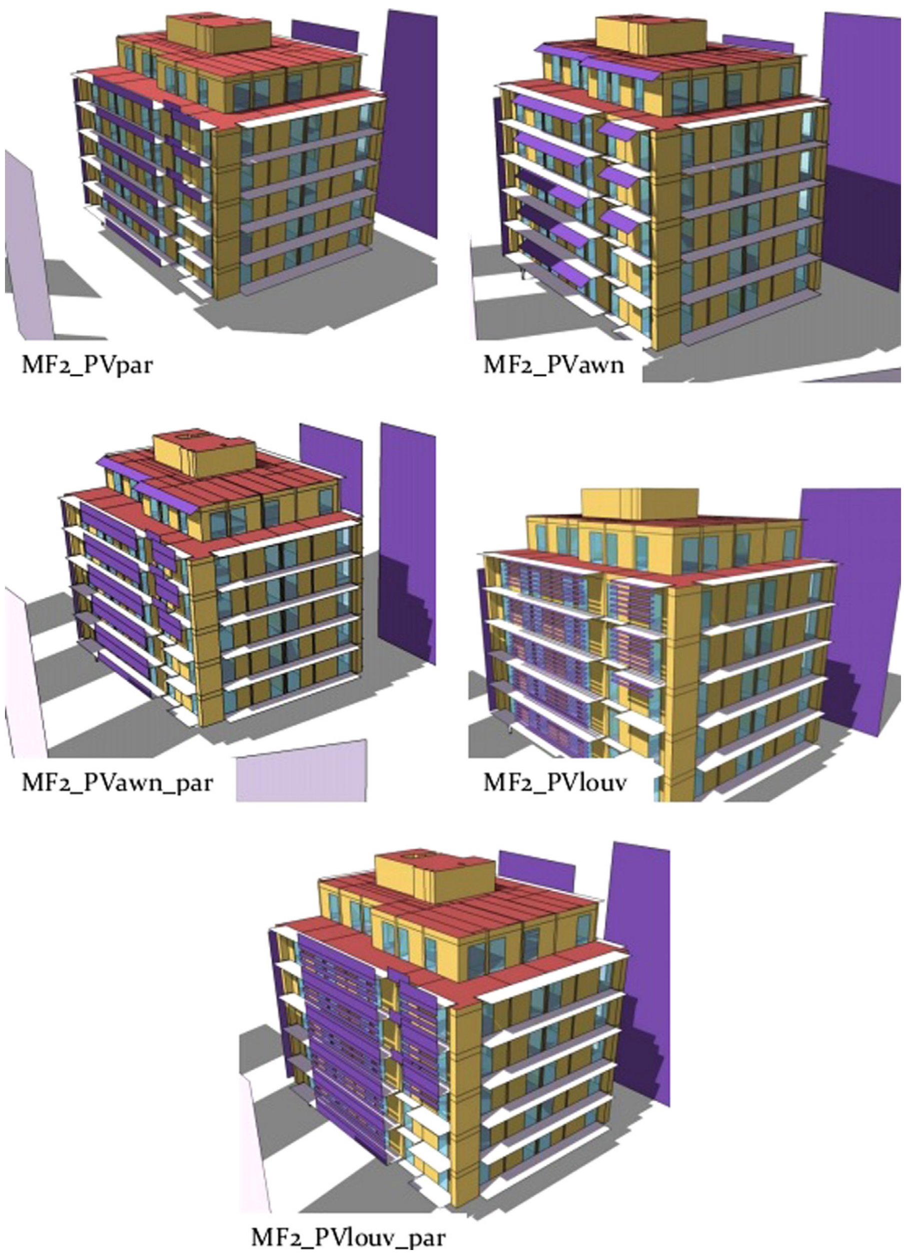

Fig. 7. 3D graphics of the simulated façade PV systems; indicatively for the building MF2.

was focused on the rest of the simulated façade scenarios. As regards MF1 and MF1_sem.de, all façade systems increased the final energy consumptions by an equivalent level, with the opaque PV louvers combined with parapets, being the most unfavourable scenario. Based on the greater PV capacities achieved and the net energy savings, the combined system of PV awnings

Table 13
Capacities of the simulated façade PV systems for the main MF-building typologies.

Simulation scenario	MF-building typology	Capacity [kWp]	Capacity per conditioned built area [Wp/m^2]
PVpar	MF1	3.04	3.74
	MF2	7.80	2.39
	MF3	4.14	4.54
	MF4	4.63	4.36
PVawn	MF1	4.26	5.24
PVawn_trans	MF2	11.58	3.54
	MF3	6.48	7.11
	MF4	7.25	6.82
PVawn_par	MF1	7.30	8.98
	MF2	19.38	5.93
PVawn_par_trans	MF3	10.62	11.64
	MF4	11.88	11.18
PVlouv	MF1	2.66	3.27
PVlouv_movable	MF2	7.59	2.32
	MF3	5.44	5.96
	MF4	6.07	5.71
PVlouv_par	MF1	7.60	9.35
PVlouv_par_trans	MF2	20.39	6.24
	MF3	13.46	14.76
	MF4	15.05	14.16

Table 14
Average annual electricity production of the simulated PV systems.

Simulation scenario	Inclination of PV modules	Average annual electricity production [kWh/kWp]
PVpar	90°	817
PVawn	30°	1427
PVawn_trans	30°	1435
PVawn_par	90°	910
PVawn_par_trans	90°	910
PVlouv	50°	1228
PVlouv_movable	One-axis sun-tracking	1473
PVlouv_par	90°	946
PVlouv_par_trans	90°	946

Table 15
Final energy consumptions of MF-buildings - Base case scenario [5].

MF-building	DHW	Electrical appliances/lighting	Heating	Cooling	Total Final
	[kWh/m^2]				
MF1	8.84	20.43	62.02	10.78	102.07
MF2	13.92	21.49	112.78	18.03	166.22
MF3	8.38	19.38	90.23	5.58	123.56
MF4	17.10	23.65	84.70	17.69	143.14
MF1_sem.de	8.84	20.43	63.45	11.03	103.74
MF3_sem.de	8.38	19.38	101.96	6.30	136.02
MF3_de	8.38	19.38	114.59	7.08	149.43
MF4_sem.de	17.10	23.65	76.57	15.99	133.31
MF4_att	17.10	23.65	72.08	15.05	127.88

and parapets, either opaque or semi-transparent, was preferred in terms of the energy potential for these particular MF-building typologies. With reference to MF2, the façade applications contributed at similar rates to the final energy modification, with the minimum and the maximum values met in the scenarios with fixed PV louvers and combined PV louvers with parapets correspondingly. Taking into account the maximum PV capacities that can be utilized, the PVawn_par or PVawn_par_trans applications were selected as the most optimal ones, as already made for MF1 building typology. The same conclusions were also drawn for MF3 and MF4 building's typologies. Overall, the combination of PV awnings and parapets provided sufficient capacities so as to accomplish noticeable net energy savings and an efficient electricity load carrying capability. In addition its impact on the energy performance of the MF-buildings ranged at lower levels in relation to the other PV options. A more thorough overview of the energy potential predicted for the simulated PV scenarios is presented by Karteris [19].

3.4.2. *Feasibility*

The evaluation of the examined PV scenarios' feasibility was conducted by means of the simple payback period's (SPB) assessment. One could argue that the SPB is a rather simplified indicator for the profitability of an investment, given that it does not incorporate the future variations of the value of money. However, taking into account the historical fact that the PV costs had drastically decreased since 2009 and this trend seems to hold at least until today [20], the SPB was assumed safe enough, at least to lead to draw some conclusions about the feasibility of the proposed systems.

The estimation of the feasibility was divided in two phases;

(a) the first was related to the payback period taking into account only the profits gained by the generated electricity fed into the grid.
(b) the second and overall SPB also included the additional consumption costs caused due to the final energy modifications made with the integration of PVs in the MF-buildings.

The basic technical and economic data used for the appraisal are shown in Table 16 and refer to the economic conditions until 2012. The differentiation between systems with nominal capacity below and above 10 kWp was related to the tariff and the income tax rate foreseen. The average retail costs for heating and electricity consumptions were similar for all PV capacities and MF-buildings. Additionally, the mean investment capital required for all examined PVs and for six groups of capacities, is illustrated in Fig. 9. The PV costs were obtained by an extensive market research and were associated with 2011s rates of expenses for typical BIPVs and BAPVs. It is obvious that the PV louvers stood for the highest costs, due to their customized design. The maximum cost concerned especially the one-axis sun-tracking PV louvers. The PV awnings and PV parapets require much less investment capitals, a positive parameter that made them more affordable. Moreover, the effect of economy of scale reduced to a degree the costs per capacity unit, while the semi-transparent modules proved to be more expensive (on average by 8%) in all the associated façade scenarios. The higher the transparency of the PV modules, the higher the production cost for solar cells with an equivalent efficiency to that of the opaque ones'.

The SPB of the simulated PVs was initially predicted, by only considering the FiT grants obtained for the generated electricity. The results in Fig. 10 are typical for all systems. From an initial observation it is easily derived that only the PV louvers could be straightforwardly evaluated as unfeasible, since they demonstrate a payback period in excess of ten years, which in the current analysis was set as the maximum acceptable SPB. The payback period of PVpar, but also of PVawn and PVawn_par options, whether opaque or not, were satisfactory, varying from 4.4 to 9.7 years. Among them, the worst scenario was the system with the semitransparent PV awnings-parapets, with a capacity

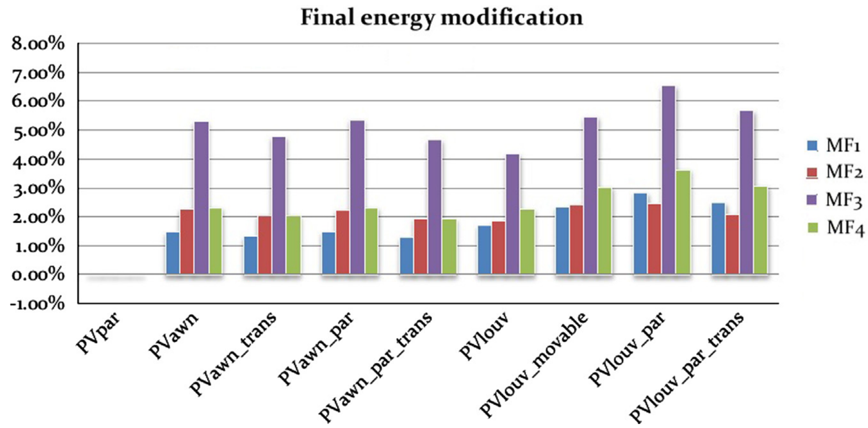

Fig. 8. Change in the final energy consumptions of MF1, MF2, MF3 and MF4 for all simulation scenarios.

Table 16
Financial data used in the assessment based on the FiT terms, tax rates and fuel costs until 2012.

PV capacities	Feed in Tariff [€/kWh]	Average income tax rate	Average heating cost [€/kWh]	Average electricity cost [€/kWh]
≤ 10 kWp (residential)	0.550	0.0%	0.084	0.081
> 10 kWp (commercial)	0.395	18.0%	0.084	0.081

between 10 to 15 kWp, whereas comparatively the best one referred to the PV awnings of 10kWp due to their optimal inclination and their better average annual energy performance. Conclusively, in terms of the FiT income, the PV louvers are definitely ruled out, thus leaving two scenarios to choose from; the PVawn and PVawn_par, with the first proving to be the most profitable application.

When it comes to the overall SPB based on FiT income and also on the additional savings or costs for the final energy consumption, the best façade application can be defined more objectively from the economic aspect, as also supported by Karteris [19]. As regards MF1 typologies, it seemed that the PVawn_par scenario had the worst impact on the SPB, increasing it by more than 50% compared to the PVawn scenario. This stemmed obviously on the one hand from the nearly 50% less electricity generated by the combined system on an annual basis, since it was simulated at a 90° inclination, and on the other hand from its investment unit cost that was equal to that of the PV awnings. In MF2 the systems that satisfied the criterion of the 10 year SPB were the PVpar, PVawn and PVawn_trans, independently from the installed capacity. The PVawn_par option, opaque or not, is acceptable only for 5 to 10kWp capacities or greater than 25kWp. It is worth mentioning that there were very significant increases of the SPB (up to 75% for small-scale residential systems) when the final energy modifications were taken into account, in addition to the generated electricity. This confirms the significance of evaluating the PVs considering the energy performance of the MF-buildings before and after the installation. Similarly of great interest observations can be made for the MF3 and MF4 building typologies. In these particular buildings, the outcomes of the SPB showed that the PV awnings represent the only viable choice. The acceptance of the other alternatives, for instance the PVawn_par scenario, is dependent on the size of the system, a variable that influenced to a great extent the economic evaluation of MF2's PV scenarios and to a lesser degree the MF1 typologies.

Conclusively, there is one beneficial installation selected from the economic aspect; the PV awnings. The latter comes to controversy with the energy potential's assessment conclusions, according to which the most beneficial solution proved to be the combined system PVawn_par. This presupposed that the discussion about the energy performance of MF-buildings with and without the PVs, should be extended by evaluating also the CO_2 emissions' savings.

3.4.3. Environmental potential

The computation of the annual CO_2 savings, if any, with PV systems in the MF-buildings, required in advance the classification of the final energy consumptions for heating, cooling, DHW, lighting and electrical appliances based on the type of the source energy used (natural gas, heating oil and electricity). Thereafter, based on the primary energy and CO_2 emission factors valid for the Greek energy system (Table 17), the total impact of all the PV scenarios on the CO_2 emissions was estimated with and without the consideration of the electricity generated by PVs. The CO_2 modification was obtained by summing all the increases and reductions in the primary energy consumptions. There is a case where the CO_2 emissions are escalated, rather than reduced, when façade PV systems are applied. In Fig. 11, the CO_2 emissions' modification is depicted for the main categories of the examined MF-buildings.

In what concerns MF1, CO_2 emissions were mitigated by 1 to 3% approximately in all the simulated scenarios, with the exception of PVpar system, which affected the energy performance of MF-buildings only when the generated electricity was considered, likewise to the energy potential's assessment. The MF1, in general, achieved the most noticeable reduction of CO_2 emissions, which was succeeded without taking advantage of the produced electricity by PVs and despite of the positive final energy modification predicted for all PV scenarios. This parameter highlights beyond any doubt the fact that the cooling loads' limitation with PV utilization is the dominant parameter for the reduction of CO_2 emissions, overcoming the heating consumptions' increase. This is a result stemming from the amplified primary energy and CO_2 coefficients foreseen by the Greek regulation for the use of electricity, which is consumed for cooling. As regards MF2, CO_2 emissions were reduced lesser, as the cooling demands' reduction was rather limited compared to the heating loads' growth. This applies also for the MF4 building typology. Nevertheless, contradictory results are noted for MF3; the ascending trend of the heating demand was so high, that it eventually surpassed the reduction of the cooling loads. As a consequence, there are no CO_2

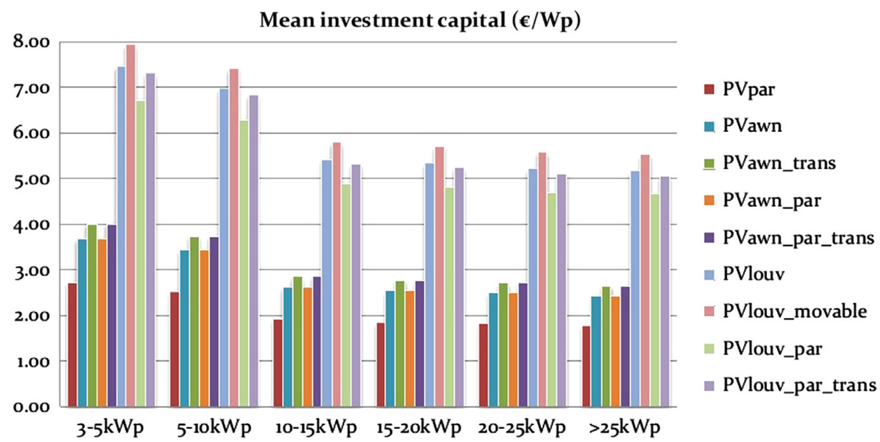

Fig. 9. Mean investment capital required for different segments of façade BIPV/BAPV systems according to their capacity [20].

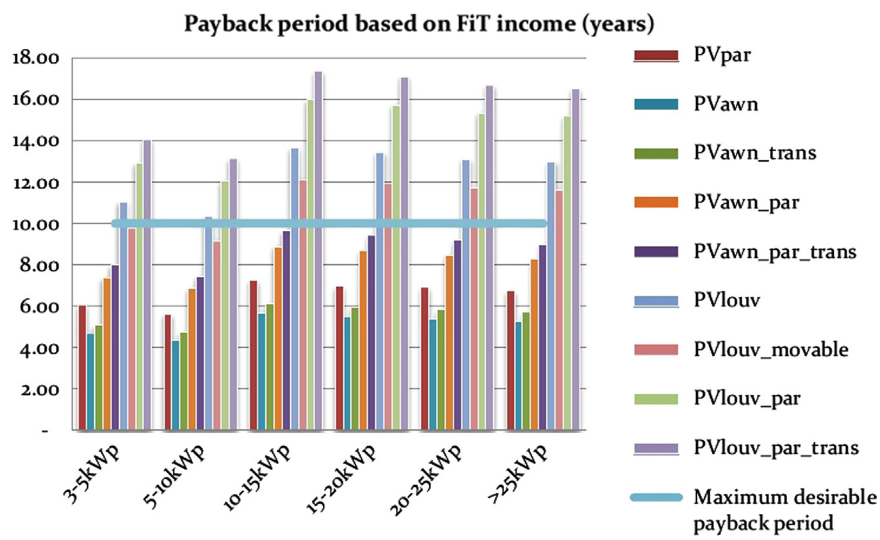

Fig. 10. Typical payback periods of different segments of BAPV or BIPV systems according to their capacity and the respective FiT of 2011.

Table 17
Primary energy and CO_2 emission factors of Greece based on the national energy mix.

Source energy	Primary energy factor	CO_2 emissions factor [$kgCO_2/kWh$]
Natural gas	1.05	0.196
Heating oil	1.10	0.264
Electricity	2.90	0.989
Liquefied petroleum gas (LPG)	1.05	0.238
Biomass	1.00	–
District heating	0.70	0.347

savings predicted for MF3, unless the generated electricity from the PVs is taken into account, as one can see in the following paragraph.

It was absolutely expected, that with the inclusion of the electricity produced by the PVs, the CO_2 emissions would be drastically decreased (Fig. 12). The best option was proved to be the combined system of the PV louvers and parapets due to the larger PV capacities modelled. However, this was only the case for MF3 and MF4, since their façade characteristics allowed for an ideal architectural integration of solar systems such as PV louvers. For the rest of the examined MF-buildings, the corresponding CO_2 savings were similar for all façade PV solutions, with the most optimal to be exemplified by the installation of PV awnings combined with the parapets.

4. The most optimal façade PV solution for the MF-buildings

Reviewing all the above results, the four systems consisted of PV louvers, fixed or movable and combined or not with parapets, were directly ruled out for the most optimal PV option for MF-building façades. Three main reasons led to this decision; the first is associated with the unaffordable high cost required and the undesirable payback periods estimated in all MF-buildings. The second concerns their contribution to the increase of the heating demand, which make the energy and ecological potential results worse than the other façade proposals, especially when the generated electricity is not taken into account in the calculations. Reversely the combined installation of PV louvers and parapets in particular represented a BIPV solution of remarkable capacity potential and electricity production. Still this case is viable when in the same time the complexity of integrating it into the existing architecture of the MF-buildings is not an issue. Based on the 3D images of MF2 in Fig. 7, one can argue that the optical indoor

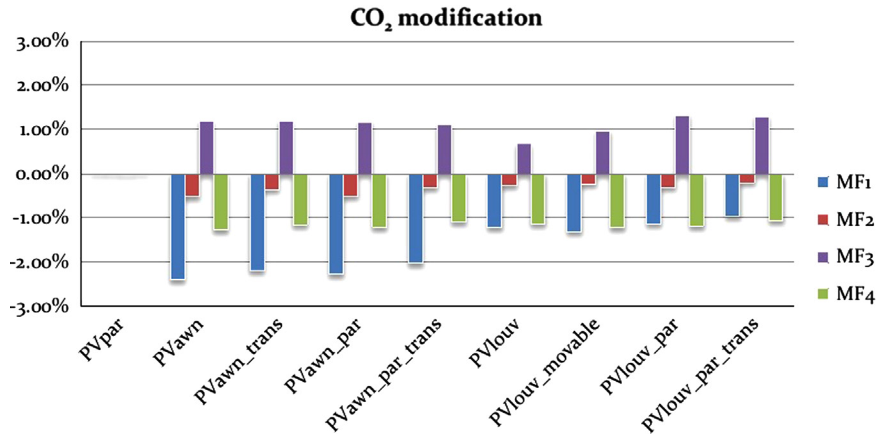

Fig. 11. Percentage modification of CO_2 emissions of MF-buildings for all simulation scenarios.

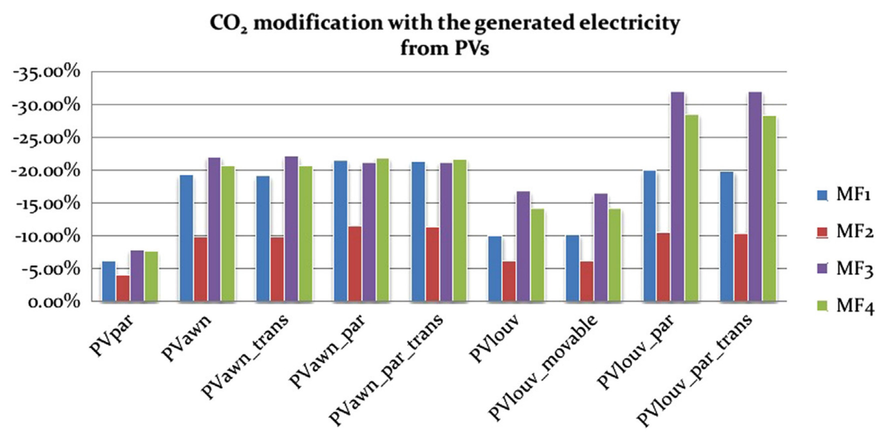

Fig. 12. Percentage modification of CO_2 emissions of MF-buildings for all simulation scenarios with the generated electricity considered.

comfort of the buildings deteriorates if the PV louvers are not designed properly. This problem becomes more intense when the louvers are installed at a 90° inclination, as one can notice for the PVlouv_par scenario.

Thus, two solutions remained to be suggested as the most optimal; the PVawn and the PVawn_par scenarios. Among them and in terms of final energy modification, the combined system of PV awnings with parapets was suggested as the most beneficial given its greater potential capacity that was almost 40% greater than that of the PVawn scenario. In that sense, this solution definitely prevails in environmental potential bearing in mind that its impact on the CO_2 emissions was better than the rest of the PV systems in most of the MF-buildings, even without considering the produced electricity.

By means of economic profitability, the PVawn_par system's investment capital is equivalent to the PVawn option, so the former is better, while it can provide the investor with greater annual profits due to its higher potential capacity. Nevertheless, the results about the predicted payback periods are contradictory; for the combined system the SPB was estimated much longer due to the relatively decreased annual energy performance per capacity unit. This aggravates the overall decision for the optimal façade application, but since the primary target utilizing solar energy should be the electricity loads' carrying capability, the economic profitability was not prioritized as a criterion. Thus, the PVawn_par system was ultimately proposed as the most optimal and efficient PV solution for the façades of the typical MF-buildings and apparently it is the system applied in the large scale analysis that follows.

5. Prediction of the solar suitable façade areas in an urban region

The solar potential prediction in the urban environment is undoubtedly a challenging task. Complex urban environments with various building block densities and miscellaneous building elevations, as well as limited available construction data about most of the urban regions, originate the difficulties involved in the solar potential approximations. In the case of Greece, until 2012 only one thorough study had been published about solar applications in the residential building sector and especially for PVs [2], mainly due to the lack of available data about Greek urban fabrics.

This section's major objective is to present a simplified methodology for the evaluation of solar architecturally suitable areas of façade surfaces in typical MF-buildings. An empirical rule, with which shading effects can be predicted based on the urban layout, the street canyons' widths and the buildings' elevations, was used after incorporating it in the GIS tool within the urban scale calculations. The solar architectural availability of the façade surfaces is apparently interdependent with the typical façade PV applications that were discussed in the previous sections.

The solar architectural potential estimation of the available façade areas is a more composite process compare to the roofs' elaboration, due to the individual architecture of each building but also because of the heterogeneous urban layout, which has a profound impact on the insolation and leads to difficulties in predicting detailed shading effects. The analysis in Section 2 about the typical architectural configuration of the façades according to the buildings' date of construction, confronted to a degree the primary difficulty to account

for the architecturally suitable areas in the residential stock, as long as it linked construction constraints for PVs with the building classes of the MF-buildings. The next necessary step is to establish the empirical rule of estimating the shaded façade areas. This was accomplished by applying basic principles of solar theory and using the appropriate available data about the elevations of buildings and the widths of street canyons in the GIS maps of Thessaloniki.

Key elements for the proposed methodology are the urban built density, the building site layouts, the buildings' orientation and number of the storeys as well as the street canyons' shape, direction and width. Fortunately, these data are generally available in digitized maps thus can be elaborated in the GIS environment. Variables related to the façade configuration itself (e.g. fraction of openings, dimensions of overhangs and fins) were already determined with the typical façade PV applications. Still, the extents of reciprocal shading effects between buildings remain unknown, whilst the calculations for the solar suitability of available façade surfaces should be conducted to comply with the criterion of PV systems' maximum performance during the winter solstice.

The current model is highly related to Robinson's work [6]. In particular, it involves the application of well-known solar techniques' equations. More specifically, the Sky View Factor (VS) of each façade has to be estimated, namely the exposed vertical surface area to solar radiation and with a free view to the sky vault. For that purpose, the Vertical Solar Angle (VSA) for a set of façade orientations and daytime intervals during the year should be predicted.

The VSA can be computed based on specific solar altitude and azimuth for a specific time instance, façade orientation and geographical latitude, in this case that of the city of Thessaloniki. Moreover, the criterion of the maximum performance of the PV systems during the winter solstice must be implemented. Therefore, the façade surfaces that were not orientated near south were presumed as unsuitable and inefficient for PVs and excluded from the proposed analysis. Finally, the façades not facing a street were also ruled out of the elaboration. Inevitably, there is an embodied, however small, error in the proposed calculation method, which can be solely dealt with dynamic shading modelling. It concerns the assumption that the shadings are predicted only for a time instance during the winter solstice and not progressively. In other words, based on the façade orientation, a certain time is defined for the shading calculations, e.g. for south orientation with azimuth between -22.5° and $+22.5^\circ$, the time instance examined during the winter solstice is 12.00 h, whereas for southeast orientation with azimuth -45° to -22.5°, the time instance is 10.30 h.

Ultimately, the solar architecturally suitable façade (S_a) areas were approximated taking into account the following equation [6]:

$$S_a = (G_a - Sh_a) \times A_{af} = [G_a - (Fac_{width} \times (h_{io} - (d \times \tan(VSA))))] \times A_{af} \tag{1}$$

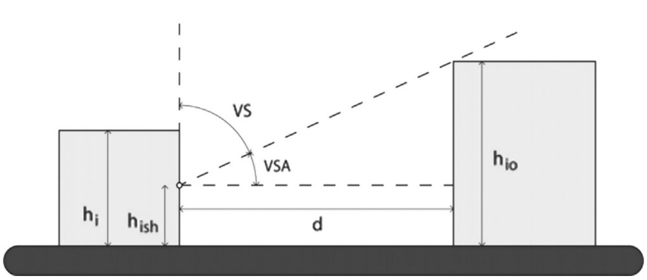

Fig. 13. Geometric definitions of VS factor, VSA angle, distance "*d*" between opposite buildings and heights (h_i and h_{io}) of the buildings for a specific point on a vertical surface [6].

where,

S_a is the solar architecturally suitable façade areas of a building unit,
G_a is the gross area of the façade,
$\mathrm{Sh_a}$ is the shaded façade area,
A_{af} is the architecturally suitable area fraction based on the MF-building class and the respective PV application (see Table 7),
$\mathrm{Fac_{width}}$ is the façade's width,
h_{io} is the height of the opposite structure to the building unit across the street,
d equals the street's width and
VSA is the Vertical Solar Angle.

The geometric definition and graphical depiction of the VS factor, VSA angle, distance "*d*" between opposite buildings and heights (h_i and h_{io}) of buildings for a specific point on a vertical surface is illustrated in Fig. 13.

The VSA is defined based on the solar altitude a and the Horizontal Solar Angle (HSA) [7] as follows:

$$VSA = \tan^{-1}\left[\frac{\tan(\alpha)}{\cos(HSA)}\right] \tag{2}$$

The HSA is estimated according to the equation:

$$HSA = |\gamma_s - \gamma| \leq 90^0 \tag{3}$$

where,

γ_s is the solar azimuth for a specific time during the day, namely the angle on a horizontal plane between the due-south direction line and the horizontal projection of the sun's rays and
γ is the façade's azimuth (orientation) related to north-south direction.

Eventually the solar azimuth and altitude are predicted for the specific time instances during the winter solstice [6]:

$$\gamma_s = C1{*}C2{*}[\sin^{-1}(\sin(\omega){*}\cos(\delta)/\cos(\theta z))] + C3{*}180{*}(1 - C1{*}C2)/2 \tag{4}$$

and

$$\sin(a) = \sin(\delta){*}\sin(\varphi) + \cos(\delta){*}\cos(\varphi){*}\cos(\omega) = \cos(\theta z) \tag{5}$$

where,

ω is the daily solar declination, which is based on the hour of the day and equals the angle between earth-sun line and the meridian plane,
δ it the annual solar declination, which is based on the day of the year and equals to the angle between the earth-sun line and the equatorial plane,
θz is the zenith angle that depends on the geographical latitude and equals to the polar angle between the earth-sun line and the local zenith and
C1, C2 and C3 are coefficients obtained based on the daily solar declination ω value.

Overall, the S_a areas' estimation of façade surfaces is a combination of two parallel conducted processes;

(a) the first refers to the connection between the building classes of Tables 3 and 4 and the MF-building polygons in the GIS map, in order to determine their architecturally suitable area fractions (A_{af}) based on Table 7 and the specified PV application.
(b) The second foresees the implementation of the empirical rule to estimate the unshaded façade areas during the winter solstice.

It should be reminded that in the following large scale analysis, only the optimal façade PV solution for the MF-buildings was examined.

6. PV potential estimation in the case study area using the GIS tool

The proposed methodology was implemented on the second largest city of Greece, Thessaloniki, in order to predict the façade PV potential. Two goals were finally reached;

(a) the methodology was effectively utilized in combination with GIS application, thus it demonstrated a significant flexibility, which allows for its multiple uses on various urban regions, if the appropriated spatial and statistical data are available.

(b) Secondly, the outcomes of the solar potential evaluation of the MF-building façades were linked successfully to a large-scale built area, that of a whole city region.

Table 18
DSM characteristics used in the case study.

Dataset characteristics	Specifications
Data type	*Digital Surface Models* (*DSM*)
Pixel resolution	0.80m
Quadrangle area extent	960 m*760m
Reference system of the map tiles	ITRF, 1:1000 scale
Format	ESRI Floating Point Grid
Geometric accuracy	RMSEz $\leq$ 0.60 m
Vertical accuracy	1.18 m, at 95% confidence level
Number of quadrangles acquired	93
Dataset volume	0.433 GB

6.1. GIS analysis step 1: prediction of the shading effects

The first step of the developed methodology was to organize the spatial dataset within a GIS environment. All the analysis on the maps was performed in commercial GIS software, ESRI ArcGIS 9.3 for the entities and polygons of the 2 cities. The Digital Surface Model (DSM) raster maps were provided in ESRI ASCII grid, projected to the HTRS07 (Hellenic Terrestrial Reference System 2007) geodetic reference system which is a realization of ETRS89 (European Terrestrial Reference System 1989) (Table 18).

As the DSM quadrangles were originally covering very small areas, a mosaic procedure was followed. The building footprints map was imported from DXF format to ESRI coverage which is a georelational data model that stores vector data, containing both the spatial (location) and attribute (descriptive) data for geographic features. The coverage file can have topology, which allows determining relationships between features. The same procedure was carried out for the city blocks' map as well as for the street network layer. Later on the analysis the coverage files have been converted to the most common shapefile (shp) file-type, which is a popular geospatial vector data format for geographic information systems software and especially for ESRI GIS software.

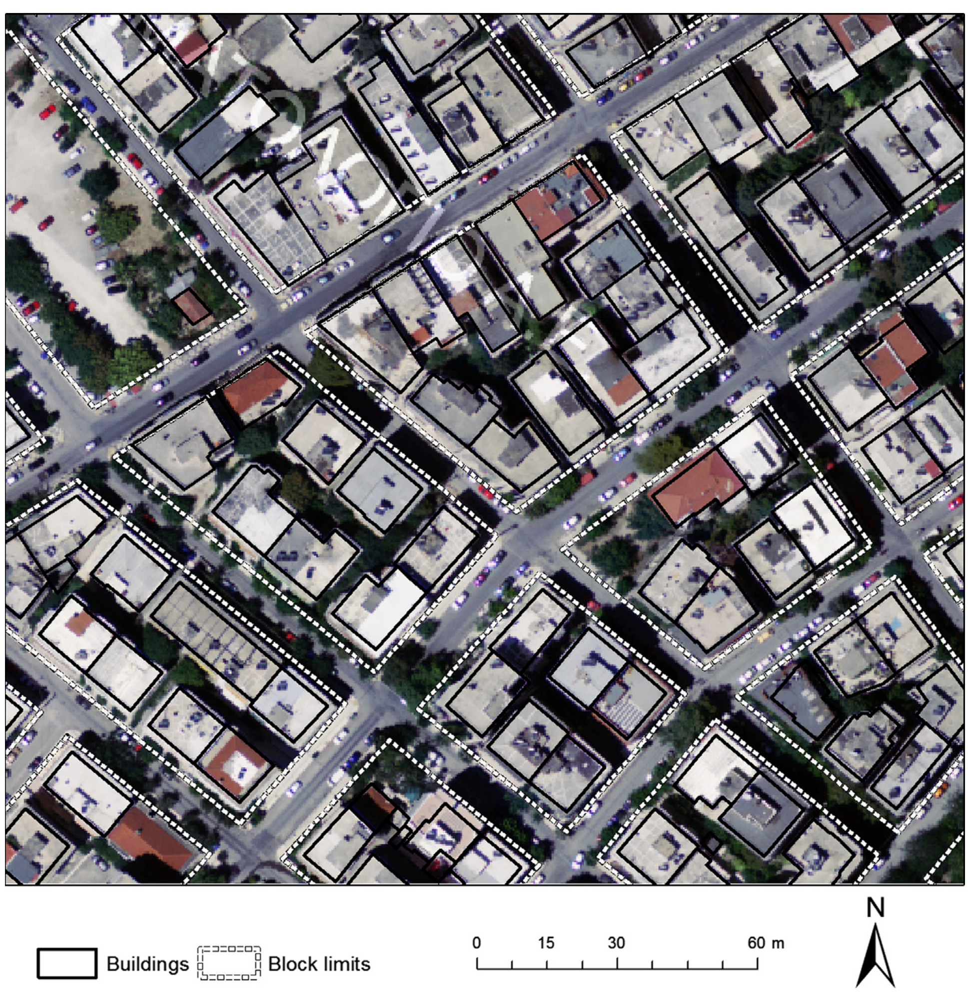

Fig. 14. The block limits polygons were overlaid upon the building footprints layer.

In order to associate each block to its buildings, the polygons representing block limits were overlaid upon the building footprints map (Fig. 14). In this way it became possible to spatially associate each entity of the city plan to the block it belongs to. Next, height information for each building was extracted from the DSM dataset. An issue that had to be overcome was the lack of a Digital Terrain Model (DTM) with better or similar resolution and accuracy to the DSM, in order to get the actual building height. Hence, based on the zonal function available within the Spatial Analyst extension toolset, height value found within each block was originally accounted for, based on the assumption that within each block, the minimum value corresponds to open ground height value. The validity of this assumption was assessed following visual interpretation of the very high resolution ortho-images. Subsequently the height of each building was calculated by the subtraction of the (zonal) mean building value from its corresponding block minimum height value.

The contiguous buildings were then identified, based on the existing polygon topology of the building coverage and the topological concept of contiguity that allows the vector data model to determine adjacency. The line feature class inherent within the building coverage was the basis for the calculation of the Euclidean allocation. Euclidean allocation produces a grid where each empty cell is assigned to the source it is nearest to. The nearest source is determined by Euclidean distance.

Based on this procedure, allocation zones resulting from line features belonging to the same building or to the same block were omitted from the analysis, retaining thus only the street facing segments of each building i.e. the façades. The orientation of each segment was estimated and then an SQL query was used for selecting façades with the desirable orientation (within 45 degrees from South direction) to maximize solar gains (Fig. 15). From the spatial allocation procedure, previously described, opposing façade pairs' distance was also calculated (Fig. 15). For each building the façades with a similar orientation (i.e. NE, N, NW, etc) were grouped together, as one can indicatively see for the Municipality of Kalamaria in Fig. 16.

Finally, all the above obtained data were used for the prediction of the shading effects from the surrounding built environment, which led successfully to the solar architecturally suitable façade areas, by applying Eq. (1).

6.2. GIS analysis step 2: map elaboration

Data availability combined with accurate digitized GIS urban maps is undoubtedly the most crucial parameter to efficiently apply the presented methodology for solar potential examination in urban areas. In this case study, all the elaborations developed in GIS environment relied on spatially explicit large scale maps of the building footprints and city blocks for the two largest municipalities of the region of Thessaloniki [3,21,22]. To assess the reliability of the maps, they were overlaid with large scale

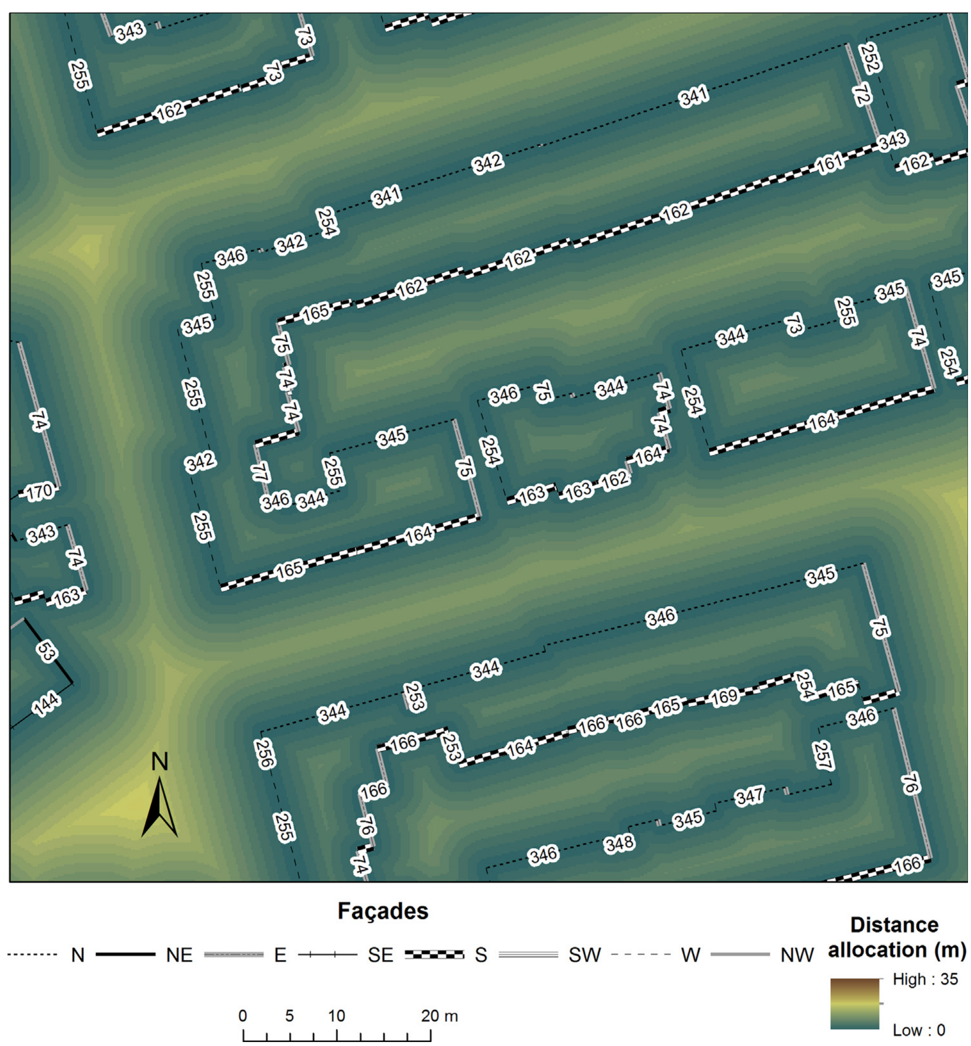

Fig. 15. GIS algorithm implementation for calculating precise orientation of street facing façades as well as the distance allocation among opposite façade pairs.

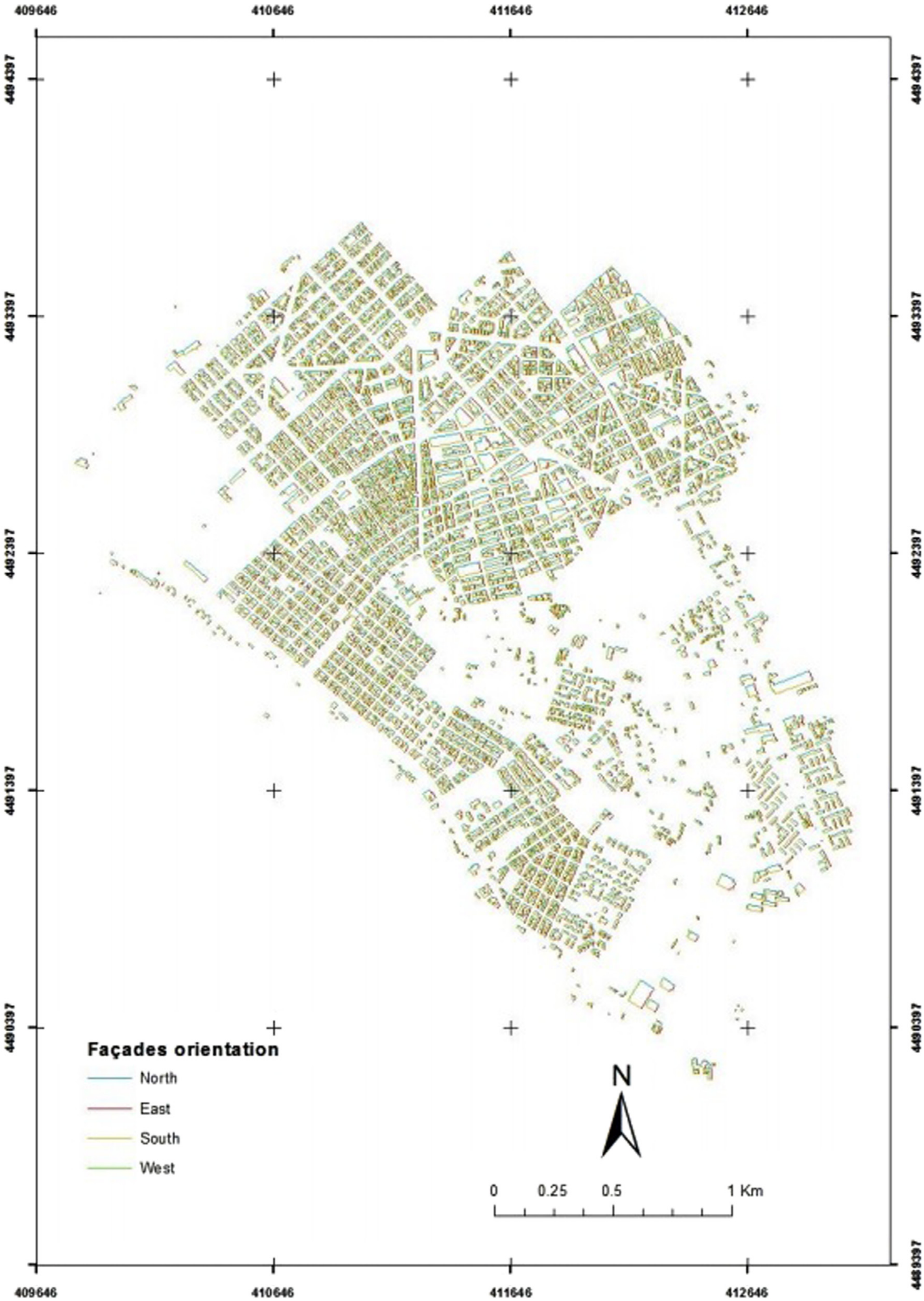

Fig. 16. Façade orientation grouped in 4 major classes (N, E, S and W) for the Municipality of Kalamaria.

orthoimagery over Greece (20cm spatial resolution), acquired in 2007 by Ktimatologio S.A. [23]. Although the city plan of the Municipality of Kalamaria was found to be very reliable in terms of spatial accuracy and information content, in the case of the Municipality of Thessaloniki errors in the building footprints digitization were noted. The spatial database of the city plan maps were enriched with census information, available either on building unit or block level, about land uses, buildings' elevations, construction systems, dates of construction, as well as socio-economic and population data, some of which were obtained by the technical authorities of the municipalities but most of them were acquired from the Hellenic Statistical Authority [3,22].

As far as spatial analysis was concerned, the ESRI ArcGIS 9.3.1 environment was used at first for processing and analysing the urban datasets. The Trimble eCognition 8.7 that is mostly employed within the framework of the GEOBIA (Geographic Object-Based Image Analysis), a sub-discipline of GISscience [24], was also used for the buildings' elaboration in both municipalities. The eCognition software is usually applied for segmentation and object-based classification of remote sensing images, while it is suited and possesses the potential to be adopted widely by end-users to build landscape level-solutions for environmental and social studies with object based investigation using non-image spatial data [25]. Within the eCognition 8.0 classification framework, multiscale representation of environmental phenomena is feasible and the discrimination of classes of interest relies on object values of each individual object (i.e. building, block, city districts) operating in the semantic hierarchy and based on a large set of features that can be calculated and provide diverse information about its spectral, textural, spatial and contextual properties [26].

Due to digitization errors in the building footprints map especially in the case of the Municipality of Thessaloniki, attached buildings within row construction system, were depicted in the city plan as nearly detached. Therefore, a viable solution for the classification of the buildings was the use of neighborhood-related information of the different footprints. To generate objects corresponding to the building footprints, fine resolution (0.1 m) raster images covering the whole extent of the municipalities were generated with ArcGIS Spatial Analyst.

In the next step, the image was imported within the eCognition software along with the city's buildings and blocks vector datasets for segmenting the image. Following, the bi-level segmentation, objects at the lower, fine scale level were classified based on the land use values included in the attribute table of the vector dataset (buildings, open spaces, streets, etc). Then, fuzzy realization of the class-related object features (namely distance to buildings, relative area of buildings and amount of buildings within a certain distance) were used to classify buildings. Information of the lower level was transferred to the upper, coarser level of city blocks, where each object-block received information from its sub-object regarding the relative area and number of each class. Finally, the classification results were exported in a vector format to the ArcGIS environment and used in the subsequent modelling of the solar potential evaluation.

6.2.1. GIS analysis step 3: MF-buildings' classification

The 3rd step of the present large-scale solar potential analysis regarded the connection of the building classes of the MF-buildings with the GIS database of the case study area. The building classes were also discriminated in sub-categories, in correspondence with the built form of the buildings, while they were already examined in the previous section for their energy consumptions with or without integrated PVs on the façades. The connection between the building classes and the building units of the case study area allowed for the successful prediction of the CO_2 savings by PVs and their attribution to the residential building stock of Thessaloniki's urban region. The dates of construction along with the buildings' uses were acquired by the Hellenic Statistical Authority whereas the built forms of the buildings were recognized by the GIS digitized maps.

A 83.53% of the building sample in the Municipality of Thessaloniki is represented by residential buildings, either strictly residential or mixed use, indicating an obvious consistency with relevant studies concerning the elaboration of national statistical data [2,27]. In addition, the majority of the buildings in the Municipality of Thessaloniki, especially those constructed before 1980 (Class B), do not have a Pilotis. In the case of Kalamaria, a 93.3% of the studied sample refers to absolute residential use, whilst the percentage of buildings with Pilotis floors is raised. Unlike the results concerning the Municipality of Thessaloniki, the majority of the buildings were constructed during the time period 1960 to 1990. Therefore, the Class C becomes more prevalent, equivalently to the Class D, which stands for a 17% of the building stock. Moreover, in the case of Kalamaria, the majority of the detached buildings refer to the semi-detached system, given that most of the MF-buildings were constructed in pairs.

With respect to various typological features, the MF-buildings were eventually linked to the four proposed building classes and their sub-categories (Table 19).

6.2.2. GIS analysis step 4: PV capacities on the façades

The 4th step of the solar potential analysis regarded the prediction of the solar architectural suitable areas on the building

Table 20
PV capacities estimated for the MF-building façades.

	PV capacities on façades (kWp)	Amount of buildings	Building stock fraction
Municipality of Thessaloniki	0.0–3.0 (unsuitable façades)	24903	96.98%
	3.0–5.0	46	0.18%
	5.0–10.0	76	0.29%
	Over 10.0	654	2.55%
	Total	25,679	100%
Municipality of Kalamaria	0.0–3.0 (unsuitable façades)	5694	79.88%
	3.0–5.0	102	1.43%
	5.0–10.0	238	3.34%
	Over 10.0	1094	15.35%
	Total	7128	100%

Table 19
Fractions of the building classes in the Municipalities of Thessaloniki and Kalamaria [2].

Municipality of Thessaloniki								
MF1	MF1_sem.de	MF2	MF3	MF3_sem.de	MF3_de	MF4_att	MF4_sem.de	MF4
21.28%	11.13%	20.88%	5.83%	5.77%	5.20%	3.60%	1.82%	4.19%
Municipality of Kalamaria								
MF1	MF1_sem.de	MF2	MF3	MF3_sem.de	MF3_de	MF4_att	MF4_sem.de	MF4
3.35%	12.50%	22.13%	21.41%	3.24%	9.66%	1.61%	5.08%	10.53%

Table 21
Final energy savings of the façade PV systems; Building frequencies (%) regard only the residential building stock with the predicted PVs.

Amount of MF-buildings	Building frequencies within the residential building stock with the predicted PVs	Final energy savings
Municipality of Thessaloniki		
196	25.21%	≤ 10%
175	22.50%	≤ 20%
107	13.74%	≤ 30%
75	9.61%	≤ 40%
50	6.39%	≤ 50%
38	4.85%	≤ 60%
39	4.97%	≤ 70%
29	3.69%	≤ 80%
25	3.17%	≤ 90%
46	5.88%	> 90%
776	100.00% (3.02% of the total building stock)	
Municipality of Kalamaria		
235	16.38%	≤ 10%
344	23.98%	≤ 20%
248	17.29%	≤ 30%
151	10.52%	≤ 40%
121	8.43%	≤ 50%
77	5.36%	≤ 60%
70	4.87%	≤ 70%
62	4.32%	≤ 80%
39	2.71%	≤ 90%
88	6.13%	> 90%
1434	100.00% (20.12% of the total building stock)	

Table 22
CO_2 savings of the façade PV systems; Building frequencies (%) regard only the residential building stock with the predicted PVs.

Amount of MF-buildings	Building frequencies within the residential building stock with the predicted PVs	CO_2 savings
Municipality of Thessaloniki		
52	6.65%	≤ 10%
93	11.93%	≤ 20%
113	14.51%	≤ 30%
74	9.48%	≤ 40%
70	8.97%	≤ 50%
52	6.65%	≤ 60%
56	7.16%	≤ 70%
44	5.62%	≤ 80%
39	4.97%	≤ 90%
187	24.05%	> 90%
776	100.00% (3.02% of the total building stock)	
Municipality of Kalamaria		
35	2.43%	≤ 10%
120	8.36%	≤ 20%
132	9.20%	≤ 30%
142	9.90%	≤ 40%
125	8.71%	≤ 50%
111	7.73%	≤ 60%
126	8.78%	≤ 70%
93	6.48%	≤ 80%
80	5.57%	≤ 90%
471	32.84%	> 90%
1434	100.00% (20.12% of the total building stock)	

unit level, filtering out the unsuitable for PV technology façade surfaces in the case study area. This process was conducted prior to the estimation of the potential CO_2 savings by PVs on the assessed as solar suitable MF-buildings.

Moreover, one only PV application was examined, as a result of the analysis in Section 4; the façade BIPV combination of parapets and awnings (PVawn_par). The PVawn_par option was preferred among multiple available BIPV solutions, given the most optimal outputs for its energy and environmental impact on the energy performance of the MF-buildings as well as its economic profitability as a grid-connected installation. The produced data about the solar architecturally suitable built areas for PVs were incorporated in the database of the GIS maps of Thessaloniki and Kalamaria and depicted by means of an evaluated potential of building units, called "Pb" [19].

The outcomes for potential façade PV capacities estimated in the case study area in association with the amount of MF-buildings are equivalently discouraging for PV diffusion. The fractions concerning façade PV applications are generally better in Kalamaria, but only for areas, where the street canyons are wide and many buildings have near south orientations (Table 20). For instance, a remarkable 15.35% of the MF-buildings in this area were found suitable for PVs on façades with capacities over 10 kWp. On the contrary, in the city centre, only a 3.02% of the building stock was evaluated as suitable for solar utilization of façades. In what concerns the aggregate façade PV potential, 62 MWp of PVs on façades were approximated by the model in Thessaloniki, while the respective sum in Kalamaria reached approximately the same levels, namely 66 MWp. This finding obtains great significance given the remarkable difference noticed between the amount of the solar suitable buildings of the two areas, which accounted for 1434 MF-buildings in Kalamaria and only 776 in Thessaloniki. In other words, the predicted façade PV systems in Thessaloniki seems by average to concern installations of larger scale compared to Kalamaria.

6.2.3. GIS analysis step 5: PV energy simulation data

The results of the dynamic energy simulations were utilized as baseline outcomes for the final energy consumptions of the existing building stock and the associate savings achieved with the predicted PV systems. The outputs were connected with the building units, based on the building classes and the construction systems that were identified by the attachments of the buildings' polygons in the GIS maps. Apparently, the analysis was performed only for the MF-buildings with the solar architectural suitable façade surfaces.

Referring to the final energy savings, they were estimated after normalizing the energy consumptions with or without PV systems with reference to the built areas. The built areas were calculated simply by taking into consideration the available elevation and roof area GIS data of each MF-building unit in the urban region of Thessaloniki. Finally, the potential CO_2 reduction was evaluated in relation to the size of the building units, so the MF-buildings could be more objectively prioritized for their suitability for PVs.

6.3. GIS results

The final energy savings of the predicted PVs demonstrated a similar pattern in Thessaloniki and Kalamaria's building sample. Taking into account the great consumptions met in the MF-buildings of Thessaloniki due their large built areas, the potential final energy savings proved to be relatively worse (Table 21) compared to Kalamaria by reaching only 10% for a 25.21% of the residential building sample and 20% for a 22.50% of the solar suitable MF-building stock. The outcomes in Kalamaria are better as long as the highest fractions of the building stock were calculated with 20% to 30% potential energy savings. Besides, the savings greater than 30% corresponds to a large fraction of the residential sector in Kalamaria, despite of the fact that the PV systems in Thessaloniki were by average approximated with higher capacities, as already mentioned.

In what concerns the CO_2 savings of the estimated PVs, as anticipated from the beginning they were evaluated higher than the final energy savings, given the generous coefficients foreseen

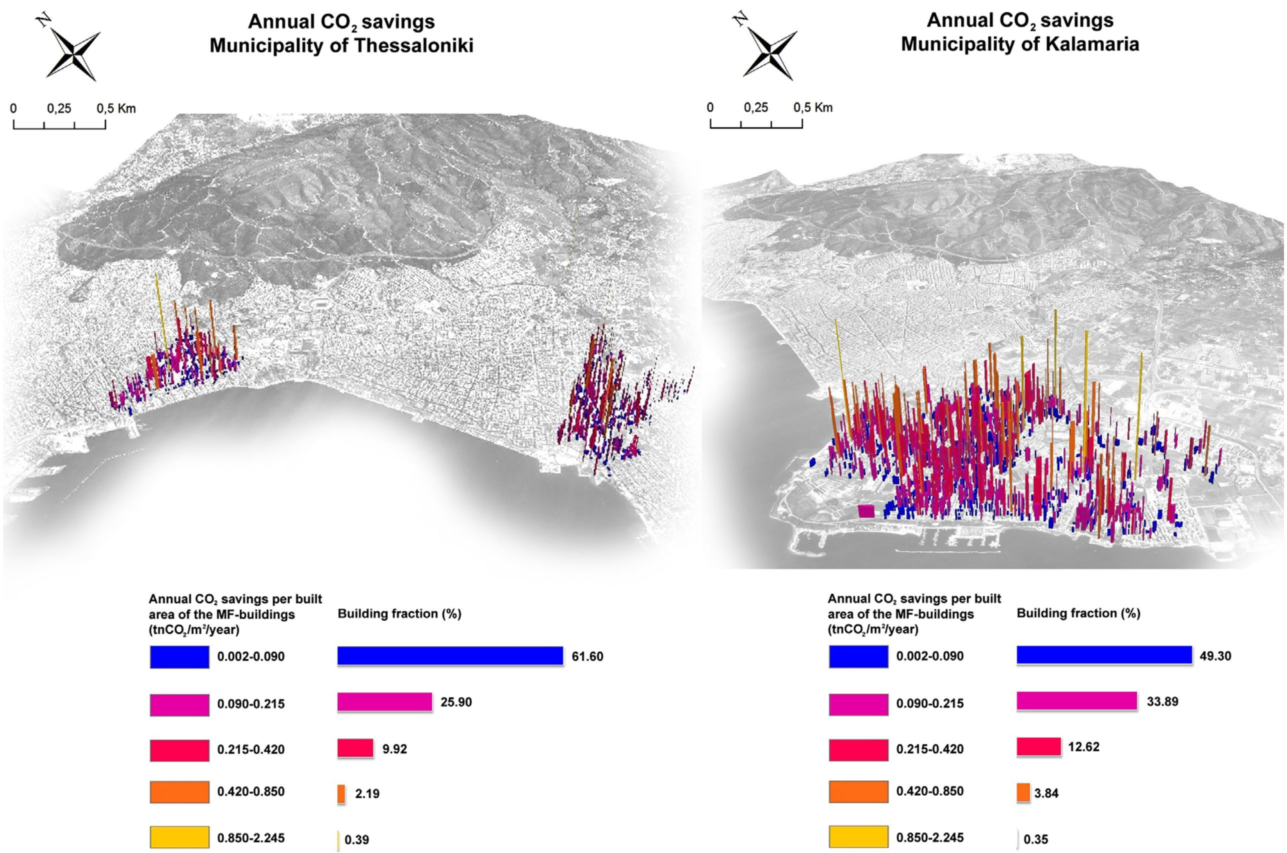

Fig. 17. Potential annual CO_2 savings per built area for the MF-buildings; Building frequencies (%) regard only the residential building stock with the predicted PVs.

by KENAK [9] for the calculation of primary electricity savings achieved with PVs. In Table 22 this is easily verified. For example, in Thessaloniki the majority of the predicted PVs, namely 24.05%, were evaluated with over 90% potential CO_2 savings. The respective fraction is amplified for Kalamaria, where a 32.84% was found to achieve the maximum CO_2 savings. Moreover, the scales of CO_2 savings are all linked with an equivalent amount of MF buildings both in Thessaloniki and Kalamaria. Still, Kalamaria demonstrates larger building sample fractions for savings over 30% compared to Thessaloniki, and for once again this is an outcome of the greater PV capacities per built area that were approximated. Overall, the 48.45% and 61.40% of façade PV systems in Thessaloniki and Kalamaria respectively could lead to total CO_2 savings above 50% on an annual basis.

Finally, similar conclusions are also obtained when it comes to the annual CO_2 savings per built area (Fig. 17). In Kalamaria for over than half of the MF-buildings (50.7%) the CO_2 savings exceed 0.09tnCO_2/m^2/year, while in Thessaloniki the same fraction is reduced to 38.1%. Concluding, the total annual CO_2 emissions' reduction with façade PVs can reach the 162 ktonnes/year in Thessaloniki, while in Kalamaria the same amount is increased up to 174 k tonnes/year.

7. Conclusions

In the present paper a comprehensive methodology to predict the PV potential of building façade surfaces was applied in a typical city of Greece utilizing geographical information systems' capabilities.

The results initially showed a contradiction between the MF-buildings' architectural availability and their overall solar suitability for PV installations. For example, the densely built urban layout of Thessaloniki resulted in a 97% of the 25,670 MF buildings to be characterized unsuitable for façade PV applications. The corresponding fraction for Kalamaria is 79.9%. This noticeable diversity emerged based on two variants: the first can be connected to the different built densities of the two areas, which define the widths of the street canyons. The second can be attributed to the favourable direction of the street canyons, namely on an east-western one, resulting in the examined buildings having mostly southern orientation. These specific streets in Thessaloniki were in their majority narrow, hence minimizing the façades' solar suitability.

On the other hand, the ways in which façades are designed contribute significantly to the final energy consumption, due to extended openings. Apart from the opening's aperture area, the facade's impact depends on its orientation, on the existence and use of shading devices, however this is also a matter of the urban area's features and the building's typology. Hence, two crucial parameters led to the greater energy and CO_2 savings outcomes for Kalamaria in comparison to Thessaloniki:

(a) The first regards the amount of the façade PV systems predicted, which was much more considerable for Kalamaria.
(b) The second parameter is related to the normalized PV capacities with reference to the built areas, which were by far greater in Kalamaria, given the lower by average elevations of its building stock.

Conclusively, the fact that a newer and less densely built area demonstrated eventually more significant solar potential results, can assist in the development of certain recommendations and proposals contributing to policy improvements for PV diffusion in the urban built environment, not only limited to Greece. For instance, the solar suitability of façades is pre-dominantly

a function of the urban built environment's layout, whilst the architecture of typical MF-buildings seems in any case appropriate enough for PV installations, independent of their individual design features. The urban layout's characteristics that need specific contemplation mainly include the widths of the street canyons with direction from east to west, given that these streets are eventually encompassed by buildings with well south orientated façades.

In that sense, PV diffusion should be encourage in the urban areas most suitable, otherwise the feasibility of the investments is questionable and this should not be encouraged by the heavily subsidized PV support schemes. Furthermore, and perhaps more important, more than four decades after the introduction of bioclimatic design principles into contemporary buildings legislation, the necessity to do this also on an urban planning level remains evident.

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